

## REPORT DOCUMENTATION PAGE

Form Approved  
OMB NO. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 30, 1996		3. REPORT TYPE AND DATES COVERED Final Progress Report	
4. TITLE AND SUBTITLE Ignition and Flame Spreading Susceptibility of Gun Propellants				5. FUNDING NUMBERS DAAL03-92-G-0020	
6. AUTHOR(S) Kenneth K. Kuo and Stefan T. Thynell					
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) Department of Mechanical Engineering The Pennsylvania State University University Park, PA 16802				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSORING / MONITORING AGENCY REPORT NUMBER  ARO 29336.17-EG	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.				12 b. DISTRIBUTION CODE  19960909 059	
13. ABSTRACT (Maximum 200 words)  This work represents the results of a series of tests on ignition and flame spreading processes of gun propellants. The overall effort was split into three tasks: (1) partially confined hot fragment conductive ignition (HFCI) characteristics of high energy, low vulnerability (HELOVA) propellants, (2) shock impact studies on HELOVA propellants, and (3) combustion of layered gun propellants. Results indicated that measured and calculated go/no-go ignition boundaries for XM49 and M43 propellants in both partially and fully confined enclosures were determined and were in a good agreement. Shock impact studies showed that ignition delay time of propellants (JA2, M30, XM39, and M43) decreased when fracture was induced upon shock wave impact. Propellants (XM 39 and M43) with brittle fracture characteristics were more susceptible to shock-wave induced ignition due to higher number of potential ignition sites. Results of layered gun propellant tests showed that the flame spreading process could significantly be affected by the spacing between adjacent layers of propellant disks. Surface groove on propellant disks can greatly facilitate the flame spreading process.					
14. SUBJECT TERMS				15. NUMBER OF PAGES	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	
				20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18  
298-102

DTIC QUALITY INSPECTED 1

**IGNITION AND FLAME SPREADING  
SUSCEPTIBILITY OF GUN PROPELLANTS**

Final Progress Report

Kenneth K. Kuo and Stefan T. Thynell

June 30, 1996

U.S. Army Research Office

ARO Proposal No. 29336-EG  
Contract No. DAAL03-92-G-0020

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Approved for Public Release;  
Distribution Unlimited.

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## FOREWORD

This project was undertaken to further our understanding of the ignition and combustion characteristics of a series of gun propellants. The overall effort was split into three tasks: (1) partially confined hot fragment conductive ignition (HFCI) characteristics of high energy, low vulnerability (HELOVA) propellants, (2) shock impact studies on HELOVA propellants, and (3) combustion of layered gun propellants. Throughout the course of this investigation, we had extensive collaborations with scientists and engineers at various government laboratories, including Dr. J. Heimerl, Mr. D. Devynck, and Mr. F. Robbins of the Army Research Laboratory, and Mr. D. Downs, Dr. T. Vladimiroff, and Dr. P. Lu of the Army Research and Development Engineering Center. We are particularly grateful to Mr. Fred Robbins who sent us a large number of newly synthesized layered propellants for study using our diagnostic facilities.

This report provides a summary of the most important results obtained in the three different tasks mentioned above. The reader is referred to the publications associated with the work conducted on this project that are listed in Section IV of this report.

## I. PARTIALLY CONFINED HFCI CHARACTERISTICS OF HELOVA PROPELLANTS

### I.1 Statement of the Problem

Raley et al.<sup>1</sup> conducted experiments using a chemical energy (CE) spall test in order to evaluate the response of candidate propellants for 105-mm tank cannon ammunition to a shaped-charge jet-generated spall attack. In these experiments, nitrocellulose-based (M30) and nitramine-based (XM39 LOVA and M43 HELOVA) propellants were employed. Previously conducted HFCI tests indicated that the M43 propellant should be less susceptible to ignition due to spall fragment-induced pyrolysis and reaction than the XM39 propellant. It was expected that similar results would be obtained with CE-spall tests using these propellants confined within ammunition cartridges. However, test firings revealed that none of the cartridges loaded with the XM39 LOVA propellant reacted when attacked by spall fragments, whereas about 25% of the cartridges loaded with the HELOVA propellant (M43) exploded after first producing smoke during fizz burning (slow cook off) for about 65 to 125 seconds. The XM39 and M43 propellants contain the same nitramine (RDX), and the only difference is that an ATEC binder ingredient in the XM39 propellant is replaced with an energetic plasticizer (EP) in the M43 propellant.

It was postulated that the difference in the conditions under which the HFCI and CE-spall tests were conducted may be the cause of the unexpected results. Specifically, the HFCI tests were conducted at constant pressures, whereas the penetration of spall fragments through the cartridge casing may lead to a pressure rise caused by an accumulation of pyrolysis products within the cartridge and subsequent gas-phase ignition among pyrolysis products. The possibility of pressure increase could be caused by a rearrangement of the granular bed, i.e., the entrance hole of the shaped-charge jet for spall fragment generation is partially blocked thus preventing pyrolysis gases to escape.

The overall objective of this study was to understand and assess the thermochemical processes controlling the ignition susceptibility of XM39 (LOVA) and M43 (HELOVA) propellants and to explain the unexpected ignition behavior of M43 propellants within confined enclosures. Such a study involved the design of a partially confined (PCHFCI) test setup for simulating the effect of gas accumulation on ignition within a cartridge damaged by spall fragments and the extension of an existing theoretical model to include the effect of the confined enclosure and binder ingredient differences.

### I.2 Summary of Experimental and Theoretical Approaches

*Experimental Approach.* A stainless steel cylinder of diameter 0.63 cm (0.25 in) was used to simulate the spall fragment. The fragment was suspended in the hot-core region of the tube furnace by the suction force produced from the vacuum in a stainless-steel tube. After the fragment reached thermal equilibrium within the furnace, the fragment was released, falling downward through an open section at the bottom of the furnace by gas filling of the vacuum. When the cylindrical fragment landed on the sample, nitrogen gas from a cylinder pushed a sliding plate which closed the opening of the guiding tube to prevent pyrolyzed gases from entering and igniting within the furnace. Closing the opening at the top of the chamber also allowed pressure buildup in highly confined test situations. The nitrogen gas line was controlled by a remote control ball valve. A wide variety of measurements was performed in the test rig while the hot fragment interacted with the propellant. These included: (a) transient temperature response within solid propellant at several locations, (b) onset of light emission and subsequent ignition of sample by a fast-response near-IR photodetector, (c) time variations of gas-phase temperatures at several locations within the enclosure, (d) pressure-time variation within the enclosure, and (e) observation of gaseous ignition and combustion processes by means of a video camera.

*Theoretical Approach.* In the theoretical portion of the investigation, an existing HFCI model<sup>2-5</sup> was extended by incorporating a reduced chemical kinetic mechanism of the XM39 and M43 propellants

and by accounting for the gas accumulation effect in the confined environment. To provide strong linkage between the modeling effort and experiment, the model was formulated to simulate the experimental test event including: (1) a uniformly heated metal particle, (2) a realistic propellant sample, (3) heat conduction induced ignition phenomena, (4) chamber pressurization, due to accumulation of gas-phase products and (5) effect of chamber confinement on go/no-go ignition boundary.

The chemical composition of XM39 propellant is: 76% of cyclotrimethylenetrinitramine (RDX), 12% of cellulose-acetate-butyrate (CAB), 7.6% of acetyltriethylcitrate (ATEC), 4% of nitrocellulose (NC) and 0.4% of ethylcentralite (EC), which is a stabilizer for the NC. In the M43 propellant, the ATEC is replaced with an energetic plasticizer which was assumed to release  $\text{NO}_2$  upon thermal decomposition. The RDX crystals are on the average 5  $\mu\text{m}$  in diameter, and are bound together primarily by the CAB and ATEC ingredients. The competing decomposition reactions of RDX are considered together with the major exothermic reaction between  $\text{NO}_2$  and  $\text{CH}_2\text{O}$ . A detailed description of the chemical kinetic scheme for ignition study of XM39 propellant is available.<sup>6</sup> The mechanism proposed by Brill and Brush<sup>7</sup> and associated kinetic data suggested by Melius<sup>8</sup> were adopted for RDX decomposition. The DSC data of XM39 obtained by Miller<sup>9</sup> were used for the liquid-to-gas conversion rate. The global kinetic rates for reactions between  $\text{NO}_2$  and  $\text{CH}_2\text{O}$  were adopted from the work of BenReuven et al.<sup>10</sup> Because of its chemical stability, the effects of EC on ignition were assumed to be negligible. Governing equations for heat conduction within the spall particle and inert heating of the propellant were recast into ordinary differential equations by the integral method.<sup>11</sup> The overall PCHFCI model consists of a total of 34 ordinary differential equations solved simultaneously by Gear's method.<sup>12</sup>

### I.3 Summary of Most Important Results

Figure 1 shows the calculated and experimentally determined go/no-go ignition boundaries for a partially confined enclosure, defined by its exhaust port area ( $A_{\text{exit}} = 3.17 \times 10^{-5} \text{ m}^2$ ). The calculated go/no-go ignition boundaries for partially confined environments, were found to be in very good agreement with the measured data. The XM39 propellant was found to be more susceptible to ignition than the M43 propellant in a partially confined environment. The reason the M43 propellant is more resistive to conductive ignition is that its binder decomposition is more endothermic than XM39, and the foam-layer ignition occurs only at an extremely high initial spall-fragment temperature.

Figure 2 presents a comparison of experimental data with calculated go/no-go ignition boundaries for XM39 propellant in different confined enclosures. Both theoretical calculations and experimental data show that the go/no-go ignition boundary of the highly confined case is lower than the partially confined case. The calculated go/no-go ignition boundaries of XM39 propellant for the range of spall fragment sizes tested are consistent with the measured values. Smaller spall fragments were not used in experimental measurement since they must be heated to temperatures beyond the maximum temperature of the furnace. Figure 3 compares experimental data with calculated go/no-go ignition boundaries for the M43 propellant in different confined enclosures. For the M43 propellant, the extent of the chamber confinement was found to have an even stronger effect on the go/no-go ignition boundaries than the XM39 propellant. For a larger size spall within a highly confined enclosure, the M43 propellant was found to be more vulnerable to HFCI than the XM39 propellant. Although the match of the highly confined case is not extremely close, calculated results show the same trend and are also useful in explaining the unexpected ignition behavior observed in shaped-charge jet impact tests of cartridges loaded with M43 propellant grains.<sup>1</sup> In these tests, penetration of spall fragments through the cartridge case could therefore lead to a pressure rise caused by an accumulation of reactive pyrolysis products such as  $\text{NO}_2$  and  $\text{CH}_2\text{O}$  within the cartridge. Exothermic reactions between these gaseous species could cause subsequent gas-phase ignition and further chamber pressurization. It is believed that the reduction of ignition threshold is caused mainly by the exothermic reaction between  $\text{CH}_2\text{O}$  and  $\text{NO}_2$  species; their

concentrations and collision rates are increased under chamber pressurization conditions. This effect is more pronounced for the M43 propellant, which generated a higher concentration of  $\text{NO}_2$  from its energetic plasticizer.

The results described above were based on an assumed thermal decomposition behavior of the binder ingredients. Rapid thermolysis experiments have revealed that the extent of decomposition of the major ingredients CAB and ATEC over the range of temperatures from 450 to 600K is quite limited. Furthermore, the model also incorporates a pressure dependent convective heat transfer coefficient as well as decomposition of  $\text{NO}_2$ . The use of these model modifications has enabled an improved predictive capability of the propellant's rate of gasification, as well as the location of the Go/No-Go ignition boundary for both partially and fully confined enclosures.<sup>13</sup> In Fig. 4, the Go/No-Go ignition boundaries for the totally confined enclosure are presented. Above an individual curve in this figure, the ignition is either observed or predicted. Examination of Fig. 4 reveals that an improved agreement with the experiments was obtained with the modification of the model described previously over the range of data acquired. This improved agreement is attributed to both improved knowledge of decomposition species and convective heat transfer to the chamber walls. In particular, knowledge about heats of formation and a smaller species conversion rate have caused the upward shift in the calculated ignition boundary. In addition, in the previous model, the convective heat-transfer coefficient was assumed to be independent of pressure, which also affected the location of the predicted ignition boundary.

## **II. SHOCK IMPACT STUDIES ON HELOVA PROPELLANTS**

### **II.1 Statement of the Problem**

Over a performance period of approximately 18 months, this research program examined another scientific issue related to the effect of shape-charge jet penetrators, namely the transfer of the impinging jet's kinetic energy on the propellant bed. As the jet enters the propellant charge, a blast or shock wave is generated at the jet tip. This shock wave propagates through the granular bed, causing both grain motion and, more importantly, mechanical deformation. The deformation process involves bending, compression and the possibility of subsequent grain fracture. The fracture could produce an increased surface area, as well as sites of localized high heating rates (hot spots), which significantly increase the vulnerability of the propellant grain. Blast wave measurement tests, with propellants whose mechanical response was effectively altered through lowered initial propellant temperatures, have established the importance of mechanical properties to the response level of the propellant.<sup>14-17</sup> The overall objective of this work was to study and to develop a better understanding of the effect of shock impact on the propellant response for several different gun propellants.

### **II.2 Summary of Experimental Approach**

The experiments were carried out using an existing shock tube facility.<sup>18</sup> However, there were two important modifications to this facility.<sup>19-20</sup> First, a portion of the driven section was modified to allow shock-wave intensification via an area reduction. For example, a Mach 5 shock wave entering the intensification section exits as a Mach 8 shock wave. Second, a new test section was designed and constructed to allow end-wall mounting of a thin, disc-shaped propellant sample. Inserts within the sample holder can be changed to vary the type of sample support in order to simulate grain-to-grain interactions. The test section is equipped with two large quartz side windows in order to gain access for either a Spin Physics SP2000 video system or a Hycam 16 mm film system. Photodetectors are also installed to allow the measurement of light emission as a result of propellant ignition.

To study the effects of fracture, the propellant sample was mounted in two different ways. Under full support, the back side of the propellant sample was completely in contact with the sample holder. Under partial support, back side of the sample rested on the sharp edge of a 90° wedge. In both configurations, the propellant was in contact with the holder around its periphery. The gun propellants studied in this work included JA2 (containing 59.5% nitrocellulose, 14.9% nitroglycerin, 24.8% diethylene glycol dinitrate, and 0.8% others), M30 (containing 29% nitrocellulose, 22.5% nitroglycerin, 47% nitroguanidine, and 2.5% others), XM39 (containing 76% cyclotrimethylenetrinitramine/RDX, 12% cellulose acetate butyrate, and 7.6% acetyl triethyl citrate, 4% nitrocellulose, and 0.4% ethyl centralite), and M43 (which is similar to XM39 except that the ATEC is replaced by an energetic plasticizer). JA2 and M30 are homogeneous propellants, whereas XM39 and M43 are heterogenous propellants.

### **II.3 Summary of Most Important Results**

In general, the conducted set of experiments revealed the effectiveness of using the shock-tube facility at generating the necessary conditions to study the effect of fracture on the shock-induced hot-as conductive ignition of gun propellants. The following represents a brief summary of the major findings.

1. Ignition delay times for all four gun propellants decreased when fracture was induced upon shock wave impact. It is believed that this fracture enhanced ignition process was caused by heating of sample edges which were exposed to hot gases behind the reflected shock. This belief is supported by the output of photodetectors which recorded the hot gas radiant emission as well as from the high-speed film which showed luminous regions in areas where fractured had occurred.
2. Propellants with brittle fracture characteristics were more susceptible to shock-wave induced ignition due to higher number of potential ignition sites. For example, sharp edges along fracture may cause an increased propensity to ignition. It appeared that M30 propellant was least susceptible to brittle behavior.
3. For the two LOVA propellants (XM39 and M43), very brittle fracture characteristics were revealed under partially supported shock-wave impact conditions. In the case of M43, the high-speed film revealed that this propellant shattered into many small pieces upon shock impact. The location of first light emission was around the edges of these small pieces and that the initial reaction zone was spread out over a large volume in a region outside the sample holder. Such brittle fracture characteristics may offset their low vulnerability features observed under HFCI conditions without the effects of mechanical damage.

## **III. COMBUSTION OF LAYERED GUN PROPELLANTS**

### **III.1 Statement of the Problem**

The primary goal sought by gun ballisticians for layered gun propellants is to improve propellant charge design for achieving the higher projectile muzzle velocity without altering the hardware of the gun system. Increased muzzle velocity can be obtained by increasing the propellant loading density in the gun cartridge or by tailoring the propellant burning surface area for optimizing progressivity in the ballistic cycle. The use of layered propellants was proposed by Horst and Robbins<sup>21</sup> as an approach to increase gun system performance.

Layered propellants utilize the difference in burning rate between the two basic propellants to accomplish the tailoring of the progressivity of the propellant charge. The favorable characteristics of

layered propellants should result in higher performance and better reproducibility for the gun system, however, a number of scientific issues must be addressed and the basic burning behavior unique to these types of propellants must be studied. The structural integrity of the interface between the two propellants should be considered. The interaction of the closely packed propellant grains, which may inhibit the flame spreading process, is also important. In this research program, the burning characteristics of composite disks (CD) comprised of a faster burning propellant M44 sandwiched between two thin outer layers of slower burning JAG were examined in closed chamber combustion experiments. The overall objective of this study was to investigate the effects of charge spacing, igniter position and the addition of surface grooves on the flame spreading and chamber pressurization processes of JAG/M44 CD propellant charges.

### III.2 Summary of Experimental Approach

Series of experiments were conducted using an interrupted burner setup. The main components of the interrupted burner assembly consist of a thick-walled, cylindrical fiberglass tube enclosed in a high strength steel case, a propellant sample holder, two end closures, an exhaust port and a surrounding O-shaped steel frame to hold the components in place. Both end closures contain ports for pressure transducers. In addition, the aft closure contains an igniter feed-through and holds the exhaust port. Placed between the aft closure and the exhaust port, variable thickness burst diaphragms were used to control the maximum chamber pressure. Ignition of the propellant samples was achieved by energizing an electric match placed within a 2.0 gram black powder bag igniter. Pressure within the chamber was measured at two locations (forward and aft) using Kistler Model 607C4 pressure transducers, each with a range of 690 MPa (100,000 psi). A third pressure transducer, located immediately downstream of the burst diaphragm, was used to identify the time of diaphragm rupture. The detailed experimental setup is given in Ref. 22.

A series of tests was conducted with different JAG/M44 CD charge configurations. Each propellant charge consisted of five annular composite disks with an outer diameter of 3.81 cm (1.5 in) and an inner diameter of 0.795 cm (0.313 in). The total thickness of each disk was 0.343 cm (0.135 in), comprised of two - 0.066 cm (0.026 in) outer layers of JAG and one - 0.211 cm (0.083 in) inner layer of M44. Each propellant charge weighed approximately 30 g (6.0 g/disk) and was ignited using a 2.0 g black powder charge. Table 1 summarizes the different propellant charge configurations used in the individual test firings. Tests CD02, 04 and 09 used thin inert spacers to artificially separate each disk leaving a 0.15 cm (0.060 in) gap between disks. No inert spacers were utilized in tests CD01, 03, 05, 06, 07 and 08, however, four small radial surface grooves were added to tests CD05, 06 and 07. These grooves, which were formed by displacing some of the JAG material to adjacent regions, create small gaps or pathways between disks that facilitate flame spreading. The depth of these grooves from the original surface position is 0.278 mm (0.011 in). The peaks created on the adjacent material rise 0.058 mm (0.002 in) above the original surface and the width of the groove from peak to peak is 0.60 mm (0.024 in).

### III.3 Summary of Most Important Results

Figure 5 shows the resulting pressure histories for two charge configurations to study the effect of inert spacing on flame spreading process. As expected, the disks with spacing reach the specified peak pressure of approximately 34.5 MPa (5000 psi) nearly 17 ms or nearly twenty-five percent faster than the disks with no spacers. This implies that the flame spreading process was impeded by the physical contact between adjacent disks. Further evidence of impeded flame spreading comes from examination and weighing of the recovered propellant samples. For the tests with no spacers, the surfaces of disks 2 through 4 and the inward facing surfaces of disks 1 and 5 remained a thin layer of JAG. On the remaining two outward facing surfaces, the burning had already progressed into the faster burning M44 material. In addition, the consumed mass for disks 1 and 5 was nearly 13 percent more (2.25 g versus 2.0 g) than the



inner three disks. For the tests with inert spacers, a thin layer of JAG was left on all surfaces of all disks. Disks 1 and 5 burned only 5 percent more mass (2.20 g versus 2.10 g) than the inner three disks. This more uniform burning suggests that the inert spacing in this configuration facilitated flame spreading. The flame spreading characteristics of the JAG/M44 layered disks have been explored by examining the effects of propellant charge spacing, igniter position, and surface condition alteration. Recovered propellant samples provided some insight to the structural behavior of the two propellants at the interface.

The same trend was observed for a similar charge comprised of pure JA-2 disks; however, only a six percent reduction in time to peak pressure was recorded. This small reduction in time was attributed to the non-flat nature of the JA-2 disks, resulting from material hardness and residual stresses originating in the fabrication process. This non-flat surface condition provides natural pathways that facilitate flame spreading between adjacent disks. JAG/M44 disks, on the other hand, are much softer than JA-2 disks and tend to conform and adhere to one another leaving few pathways for flame spreading.

Figure 6 shows that test samples (CD05, CD06, CD07) with the surface groove configuration resulted in a 10 ms or 15 percent reduction in the time to peak pressure (approx. 34.5 MPa (5000 psi)) compared to the case with no inert spacing. This implies the slight gap created by the surface grooves enhanced flame spreading without sacrificing the loading density of the charge. As also shown in Fig. 6, Tests CD05 and CD06 examined the effects of igniter position on flame spreading. The igniter charge for CD05 was positioned within the center bore and on both ends of the propellant charge. The igniter charge for CD06 was placed at one end of the propellant grain. No significant difference was observed in the time to maximum pressure for the two tests. Igniter position variability within the chamber was concluded to have very little impact on the results in this series of tests. However, igniter position would be expected to be important in a longer or larger diameter charges.

#### **IV. LIST OF PUBLICATIONS AND TECHNICAL REPORTS**

- Brown, J.J., Yim, Y-J., Thynell, S. T., and K. K. Kuo, "Regression Behavior of Composite Layered Gun Propellants", Proceedings of the 29th JANNAF Combustion Meeting, 19-23 October, 1992, Hampton, VA; CPIA Publication 570, Vol. , pp. , March, 1993.
- Brown, J.J., Thynell, S.T., and K. K. Kuo, "Regression Behavior of Composite Layered Gun Propellants," AIAA paper 93-1880 presented at the 29th Joint Propulsion Conference and Exhibit, June 28-30, 1993, Monterey, CA.
- Brown, J.J., Thynell, S.T., and K. K. Kuo, "Nonintrusive Diagnostics of Transient Regression Behavior of Gun Propellant Disks," Proceedings of the 30th JANNAF Subcommittee Combustion Meeting, Naval Postgraduate School, Monterey, CA, November 15-19, 1993; CPIA Publication 606, Vol. I, pp. 259-270, March, 1994.
- Huang, T.H., Thynell, S. T., and K. K. Kuo, "Partially Confined Hot Fragment Conductive Ignition: Part I - Modeling," Proceedings of the 30th JANNAF Subcommittee Combustion Meeting, Naval Postgraduate School, Monterey, CA, November 15-19, 1993; CPIA Publication 606, Vol. I, pp. 387-400, March, 1994.
- Huang, T.H., Thynell, S. T., and K. K. Kuo, "Partially Confined Hot Fragment Conductive Ignition: Part II - Experiments," Proceedings of the 30th JANNAF Subcommittee Combustion Meeting, Naval

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Ritchie, S.J., Wu, S. R., Thynell, S. T., and K. K. Kuo, "Shock-Induced, Hot Gas Conductive Ignition Characteristics of Solid Gun Propellants," Proceedings of the 30th JANNAF Subcommittee Combustion Meeting, Naval Postgraduate School, Monterey, CA, November 15-19, 1993; CPIA Publication 606, Vol. , pp. , March, 1994.

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Watson, T., Kuo, K. K., and S. T. Thynell, "Assessment of Dynamic Burning Behavior for JA-2 Propellant Rods," Proceedings of the 31st JANNAF Subcommittee Combustion Meeting, Sunnyvale, CA, October 17-21, CPIA Publication 620, Vol. II, pp. 247-257, 1994.

Huang, T.H., Thynell, S. T., and K. K. Kuo, "Experimental Measurements of Partially Confined Hot Fragment Conductive Ignition," *Proceedings of the Twentieth International Pyrotechnic Seminar*, pp. 445-459, July, 1994.

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Kim, E., Thynell, S. T., and K.K. Kuo, "Improvements in Gas-Phase Kinetic Modeling of Partially Confined Hot Fragment Conductive Ignition," Proceedings of the 32nd JANNAF Combustion Subcommittee Meeting, Huntsville, AL, Oct. 23-27, CPIA Publication 628, pp. 1-10, 1995.

Watson, T., Thynell, S. T., and K.K. Kuo, "Flame Spreading and Combustion Characteristics of Layered Propellants," Proceedings of the 32nd JANNAF Combustion Subcommittee Meeting, Huntsville, AL, Oct. 23-27, CPIA Publication 631, Vol. III, pp. 477-487, 1995.

Ritchie, S.J., Thynell, S.T., and K. K. Kuo, "Modeling and Experiments of Laser Induced Ignition of Nitramine Propellants," submitted to *Journal of Propulsion and Power*, March, 1996.

Kim, E., Thynell, S. T., and K.K. Kuo, "Improvements in Gas-Phase Kinetic Modeling of Partially Confined Hot Fragment Conductive Ignition," presented at and submitted for inclusion in symposium proceedings of the *Fourth International Symposium on Special Topics in Chemical Propulsion: Challenges in Propellants and Combustion 100 Years After Nobel*, Stockholm, Sweden, May 27-31, 1996.

Kopicz, C., T. Watson, T., Kuo, K. K., and S. T. Thynell, "Steady-State Burning Behavior and Thermal Profile Measurement of JA-2 Propellant," presented at and submitted for inclusion in symposium proceedings of the *Fourth International Symposium on Special Topics in Chemical Propulsion: Challenges in Propellants and Combustion 100 Years After Nobel*, Stockholm, Sweden, May 27-31, 1996.

## **V. LIST OF PARTICIPATING PERSONNEL AND DEGREES AWARDED**

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Dr. S.T. Thynell, Associate Professor  
Dr. S.R. Wu, Post-Doctoral Fellow  
Dr. C.L. Yeh, Post-Doctoral Fellow  
Dr. Y-J. Yim, Visiting Research Associate  
Mr. S. Ritchie, Ph.D. Candidate  
Mr. T.H. Huang, Ph.D. Candidate  
Mr. J. Brown, Master's Student  
Mr. T. Watson, Master's Student  
Mr. E. Kim, Master's Student  
Mr. C. Kopicz, Master's Student  
Mr. B. Kumar, M.S. Student  
Mr. C. Wilkerson, Undergraduate Student

### Degrees Awarded

J. Brown, Bachelor of Science in Mechanical Engineering, The Pennsylvania State University, University Park, PA, May 16, 1994.

S. Ritchie, Doctor of Philosophy, Department of Mechanical Engineering, The Pennsylvania State University, University Park, PA, August 15, 1994.

T.H. Huang, Doctor of Philosophy, Department of Materials Science and Engineering, The Pennsylvania State University, University Park, PA, August 15, 1994.

J. Brown, Master of Science in Mechanical Engineering, The Pennsylvania State University, University Park, PA, May 10, 1994.

T. Watson, Master of Science in Mechanical Engineering, The Pennsylvania State University, University Park, PA, May 10, 1995.

C. Kopicz, Master of Science in Aerospace Engineering, The Pennsylvania State University, University Park, PA, May 10, 1995.

## VI. REPORT OF INVENTIONS

No inventions have been reported as a result of this work.

## VII. REFERENCES

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Table 1. Summary of Test Configuration for Layered Gun Propellants

Test Number	Propellant	Spacing	Igniter Position	Surface Grooves
CD01	JAG/M44	No	End	No
CD02	JAG/M44	Yes	End	No
CD03	JA-2	No	End	No
CD04	JA-2	Yes	End	No
CD05	JAG/M44	No	Center	Yes
CD06	JAG/M44	No	End	Yes
CD07	JAG/M44	No	End	Yes
CD08	JAG/M44	No	End	No
CD09	JAG/M44	Yes	End	No

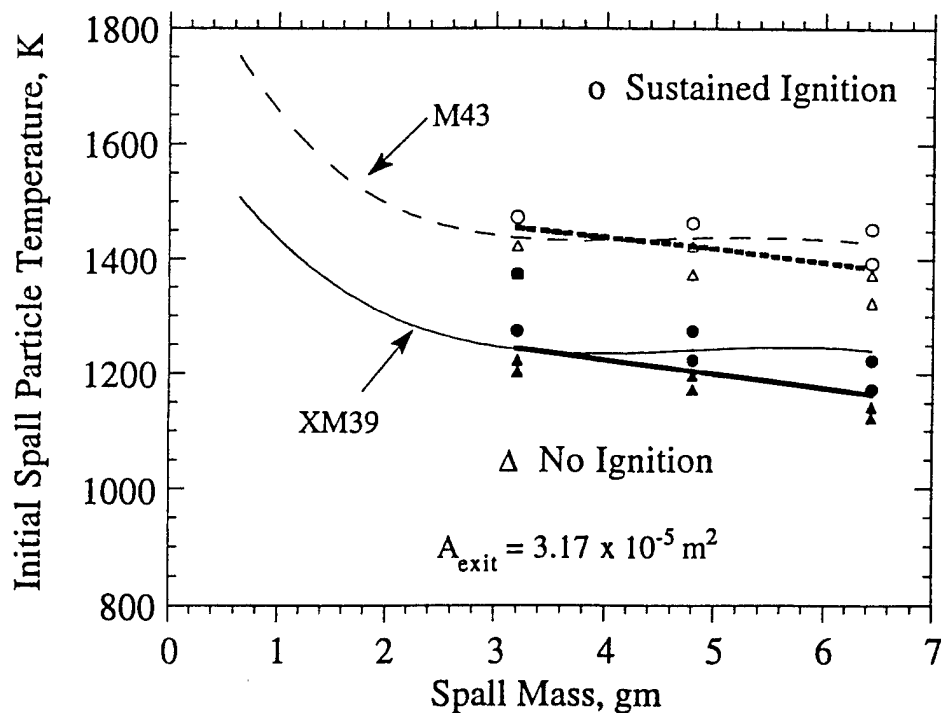


Fig. 1 Comparison of experimental data with calculated go/no-go ignition boundaries for XM39 and M43 propellants in a partially confined enclosure.

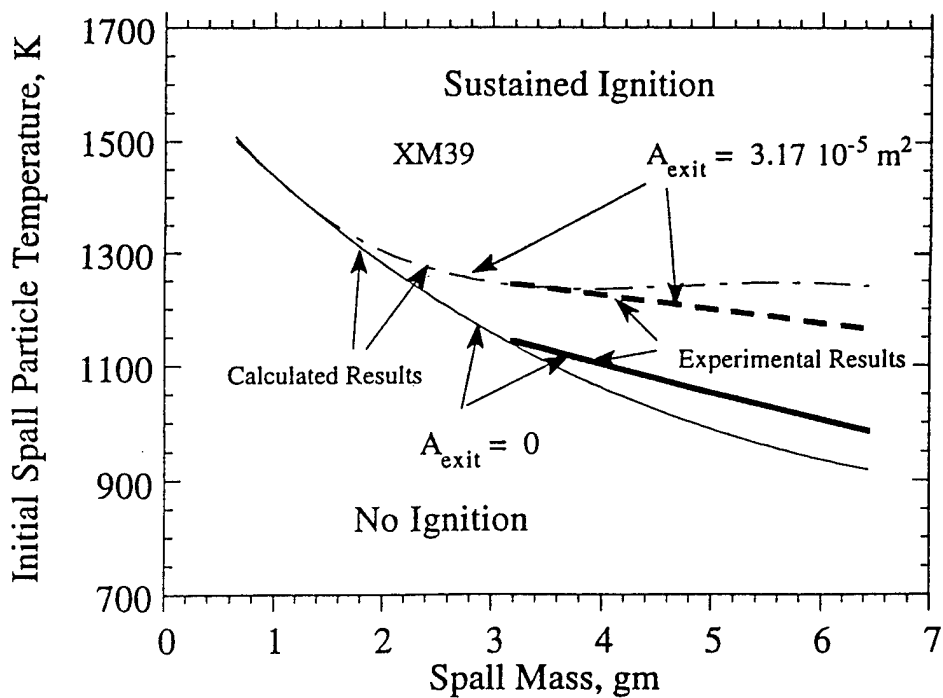


Fig. 2 Comparison of experimental data with calculated go/no-go ignition boundaries for XM39 in confined enclosures.

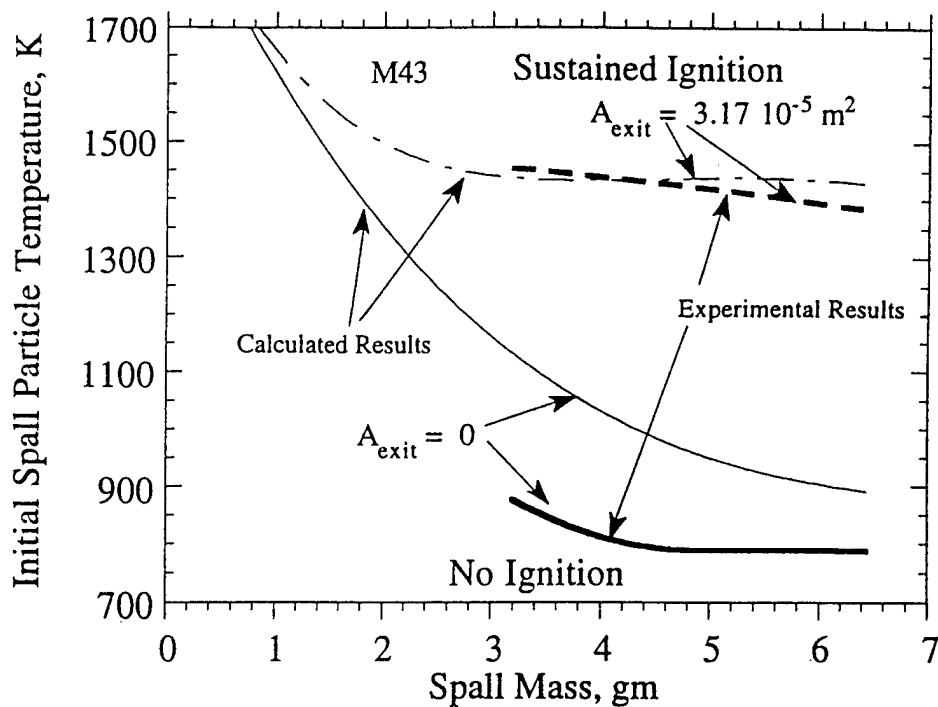


Fig. 3 Comparison of experimental data with calculated go/no-go ignition boundaries for M43 in confined enclosures.

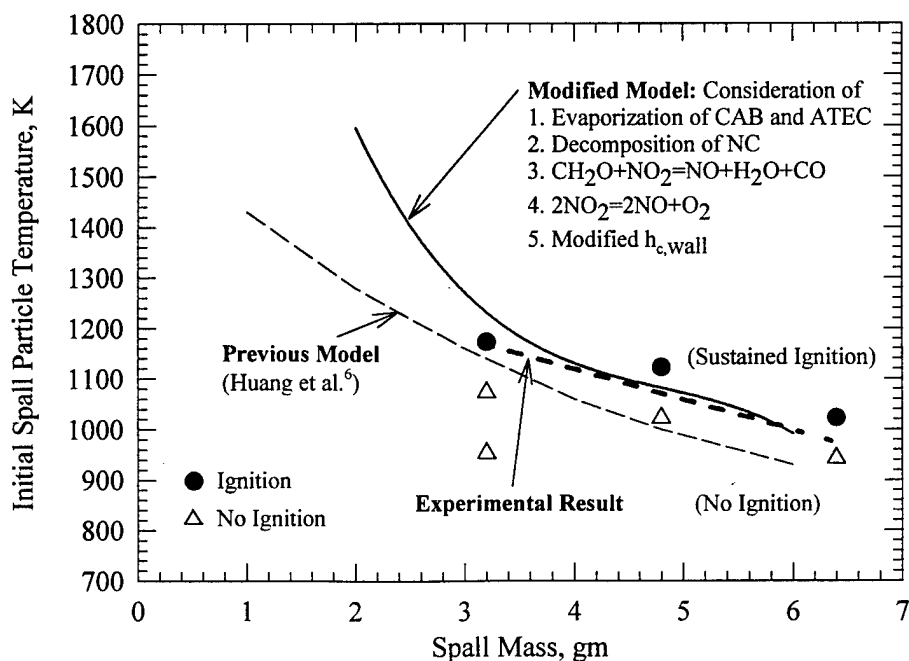


Fig. 4 Comparisons of experimental result with modified and previous calculated go/no-go ignition boundaries for XM39 propellant in a totally confined enclosure.



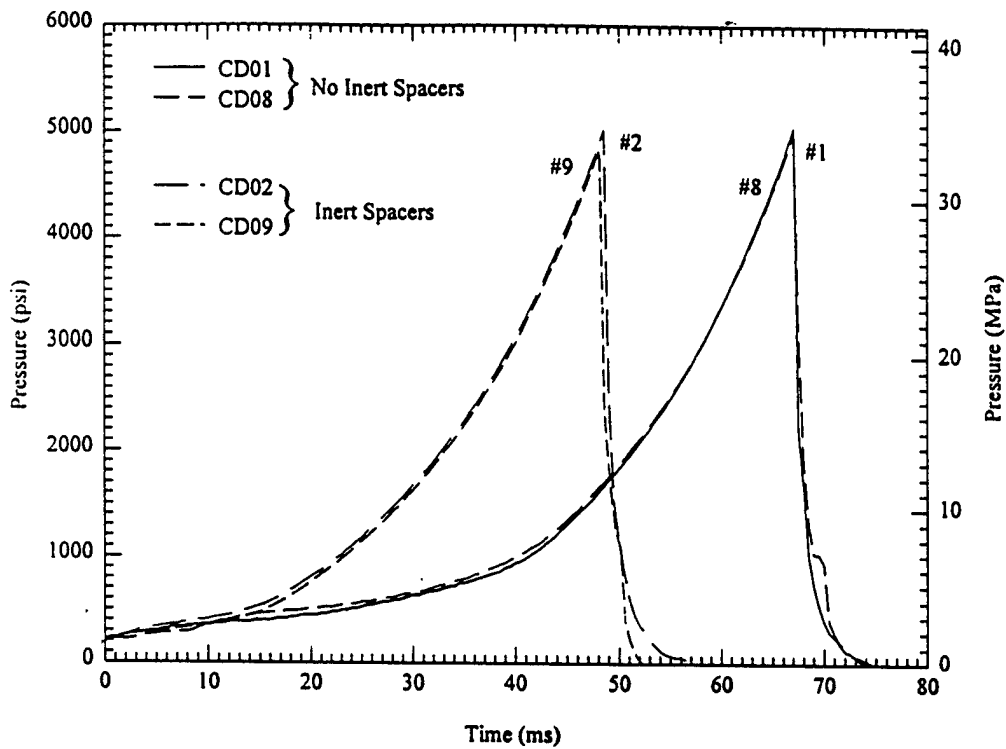


Fig. 5 JAG/M44 propellant pressure histories with and without spacers

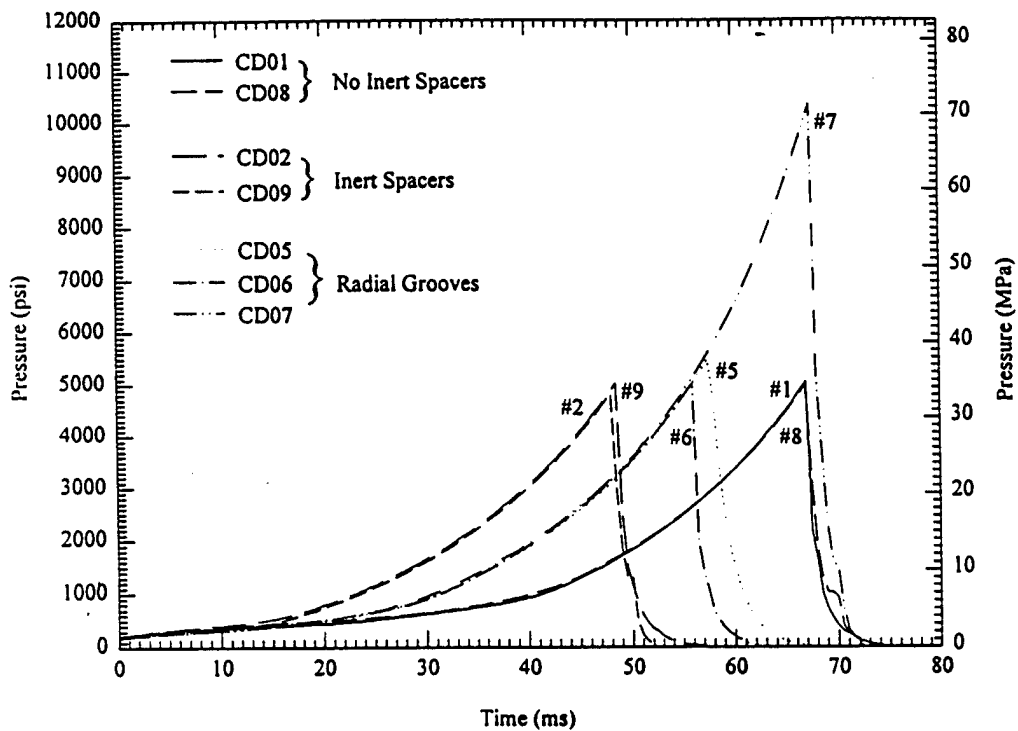


Fig. 6 Effects of inert spacers and surface grooves on pressure histories of JAG/M44 charges

# REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 30, 1996	3. REPORT TYPE AND DATES COVERED Final Progress Report	
4. TITLE AND SUBTITLE Ignition and Flame Spreading Susceptibility of Gun Propellants			5. FUNDING NUMBERS DAAL03-92-G-0020	
6. AUTHOR(S) Kenneth K. Kuo and Stefan T. Thynell				
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) Department of Mechanical Engineering The Pennsylvania State University University Park, PA 16802			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  This work represents the results of a series of tests on ignition and flame spreading processes of gun propellants. The overall effort was split into three tasks: (1) partially confined hot fragment conductive ignition (HFCI) characteristics of high energy, low vulnerability (HELOVA) propellants, (2) shock impact studies on HELOVA propellants, and (3) combustion of layered gun propellants. Results indicated that measured and calculated go/no-go ignition boundaries for XM49 and M43 propellants in both partially and fully confined enclosures were determined and were in a good agreement. Shock impact studies showed that ignition delay time of propellants (JA2, M30, XM39, and M43) decreased when fracture was induced upon shock wave impact. Propellants (XM 39 and M43) with brittle fracture characteristics were more susceptible to shock-wave induced ignition due to higher number of potential ignition sites. Results of layered gun propellant tests showed that the flame spreading process could significantly affected by the spacing between adjacent layers of propellant disks. Surface groove on propellant disks can greatly facilitate the flame spreading process.				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	